Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 78 (2015) 3246 – 3251
Energy Procedia

6th International Building Physics Conference, IBPC 2015

Comparison of steady-state and in-situ testing of high thermal resistance walls incorporating vacuum insulation panels

Christopher Baldwin*, Cynthia A. Cruickshank, Matthew Schiedel, Brock Conley

Carleton University, 1125 Colonel By Drive. Ottawa, Ontario, Canada, K1S 5B6

Abstract

Two standard test methods exist to experimentally determine the effective thermal resistance of a wall: in-situ testing to calibrate a computer simulation and steady-state testing in a guarded hot box. This paper compares results obtained using both methods on a wall assembly incorporating vacuum insulation panels (VIPs) with an experimentally determined effective R-Value of 8.21 m^2K/W using a guarded hot box. The result using a guarded hot box was lower than that using in-situ measurements paired with computer simulation as a result of the more accurate representation of thermal bridging between VIP panels using this test method. When testing in a guarded hot box, all thermal bridges, including between panels is accounted for. By comparison, an experimentally obtained thermal resistance measured at the center of a VIP panel and assumed as a constant thermal resistance across the complete VIP layer in the computer model does not account for the non-homogenous nature of a VIP layer. As a result, it was concluded that wall assemblies that contain numerous small thermal bridges like those incorporating VIP panels should be experimentally evaluated using a guarded box.

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL
Keywords: Vacuum Insulation Panels; Experimental Evaluation; Guard Hot Box; In-Situ Testing; High Thermal Resistant Wall Design

1. Introduction

In Canada, the building sector accounts for more than 29% of the secondary energy use, with almost 55% of this energy used for space heating [1]. Among residential buildings, 61.7% of the total energy use is for the purpose of space heating [1]. Residential space heating loads are predominantly a result of heat loss through the building enclosure and air leakage into the dwelling. One of the easiest methods for reducing the heating load of a building is increasing the thermal resistance of the building enclosure, while simultaneously minimizing air infiltration.

* Corresponding author. Tel.: +1-613-520-2600 x5027;
E-mail address: christopher.baldwin@carleton.ca

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL
doi:10.1016/j.egypro.2015.11.690

When installed effectively in a well-designed assembly, vacuum insulation panels (VIPs), will both increase the thermal resistance of the wall assembly and decrease unintended air infiltration. Vacuum insulation panels are thin panels (typically less than 25 mm in thickness) comprised of a porous core, sealed in a gas impermeable skin with an internal pressure of less than 5 mbar at time of manufacture [2]. Placing the core under a vacuum removes all convective heat transfer and reduces conductive heat transfer, giving VIPs a thermal resistance in excess of 10 times that of traditional low density insulating materials [2]. As such, high thermal resistance assemblies can be constructed while maintaining a reasonable thickness. Although VIPs have a high thermal resistance, they pose new challenges when integrating them into traditional building practices, predominantly as a result of the fragile nature of the panel enclosure, and as such, the entire building enclosure must be designed to accommodate and protect the panels from both the construction process, as well as the end user.

Due to the novel nature and the lack of proven, long-term evaluation, extensive thermal modelling and testing is required before VIPs will see widespread implementation within the residential building sector. Modelling VIPs pose a significant challenge as they are a non-homogeneous material, with extensive thermal bridging between panels. Because the thermal resistance of the panel is dependent on the internal pressure, it is not constant in all panels. Additionally, panels may potentially lose their vacuum, and subsequently their thermal resistance over time. This paper examines the results of a single wall design that has been experimentally evaluated using two standard test methods. The results for the different methods are compared and the correlation between methods was determined.

Nomenclature

R	Thermal Resistance (m^2K/W)	t	Time (h)
ΔT	Differential Temperature (°C, K)	A	Area (m^2)
q	Energy Input (Wh, J)	q''	Heat Flux (W/m^2)

2. Experimental testing methodologies

There are two testing methodologies to experimentally evaluate the thermal resistance of a complete wall assembly: in-situ evaluation coupled with computer modelling and steady-state testing in a guarded hot box. To date, little literature is available that examines how these testing methodologies perform when testing walls with high thermal resistances. A double-wall design, originally designed for, and incorporated into Team Ontario's entry into the U.S Department of Energy Solar Decathlon 2013 is used for this study. Figure 1 is a schematic of the wall design [3].

2.1. In-Situ experimental testing with computer modelling

This wall design was previously evaluated [4] using an outdoor test facility with complete interior climate control, and three 2440 mm by 2440 mm openings to install wall samples within. The wall design was constructed and fully instrumented. Testing was conducted based on the ASTM-C1155 standard for determining thermal resistance of building envelope components from in-situ data [5]. Thermocouples were installed between each layer

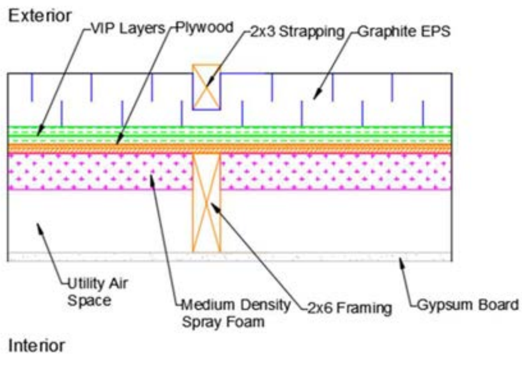

Figure 1: Plan view of wall design to be experimentally evaluated

of the wall, and a heat flux plate attached to the inside surface of the wall at key locations of the test specimen. These results were used to calibrate a thermal model of the wall developed in THERM [6], and an overall thermal resistance of the main wall components was found to be 8.9 m^2K/W [4].

The experimental evaluation and subsequent modelling provided reasonable results, however a number of limitations were observed through the test, including:

- All layers had to be modelled as homogeneous materials;
- Thermal conductivities for different materials were derived using temperature differences and the surface heat flux, with an unknown accuracy; and
- There was no control of the exterior conditions, including wind conditions and solar radiation, which caused periodic spikes in excess of 30°C while the exterior temperature was below freezing. Although, ASTM-C1155 states a sufficiently large data set will converge to provide an acceptable R-value, exterior weather anomalies remain a potential source of error [5].

As such, further study was required to determine whether the results obtained from this study were accurate, and how the in-situ testing could be adopted to provide more accurate results when testing complex wall assemblies.

2.2. Steady-state guarded hot box testing

To overcome many of the challenges that were poised by in-situ tests, a guarded hot box was constructed to experimentally determine the overall thermal resistance of wall assemblies under controlled steady-state conditions. A guarded box is a piece of equipment that contains three independent chambers. The first is the climate chamber, which simulates cold exterior temperatures, the second is a metering box which is heated to interior conditions, and the third is a guard box that is heated to exactly the same temperature of metering box, forcing all of the heat input into the metering box to go through the test specimen, and not out the sides of the metering box. The metering box has been designed to measure the heat flux through an area of the wall that is 1220 mm by 1500 mm. A schematic of a guarded hot box is shown in Figure 2. The overall thermal resistance of the wall is found by measuring the amount of heat input into the metering box, and the temperature difference across the specimen.

The guarded hot box constructed has completely controllable temperatures on both sides of the test specimen, with the climate-side able to reach temperatures below -35°C, while the interior side can be set between 21°C and 30°C. The guarded hot box removes all meteorological variances, including solar radiation and varying wind speeds the in-situ test experienced. Finally, the single biggest advantage to testing with a guarded hot box is all thermal bridges present within a wall assembly are experimentally evaluated and their influence is observed in the calculated overall thermal resistance of a wall.

3. Guarded hot box experimental approach

A test specimen was designed to represent both the wall design used in the Solar Decathlon entry, and the test specimen evaluated in the previously conducted in-situ testing and modelling study. The framing factor, which is the

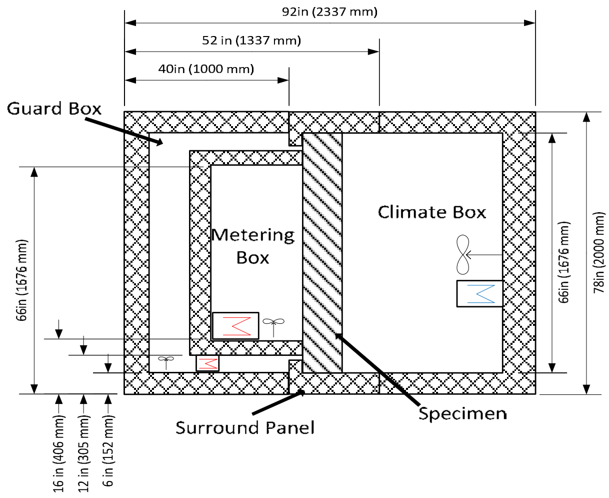

Figure 2: Schematic of the guarded hot box constructed to test wall assemblies with VIPs

area of wood studs compared to the total wall area, was matched between the final house design (16.6%) and the test specimen (16.4%). Additionally, the house contained two 100 mm strips around the entire perimeter approximately 1/3 and 2/3 up the wall to allow the outer wood studs to be fixed to the interior structural wall. This accounted for 8% of the total wall area, and as such, a 100 mm gap across the metered section of the wall specimen. Both of these were included in the wall specimen to accurately represent the thermal bridges present within the wall design, and allow the overall effective thermal resistance of the wall to be accurately determined. A schematic of the test specimen is presented in Figure 3.

The test specimen was constructed and temperature sensors were embedded within the wall, between each of the main layers so the temperature profile within the wall can also be evaluated. Additionally, a heat flux plate was installed in the center of a VIP, where no thermal bridging should occur. Additionally, 12 temperature sensors were placed on the surface of each side of the wall to determine the temperature gradient across the wall.

The climate side was set to -25°C while the metering and guard box were set to 23°C, to accurately mimic interior and winter exterior conditions in Canada, while creating a large temperature difference across the wall to promote heat transfer. After reaching the desired temperatures, the wall was then left for 24 to allow adequate time for the wall temperature gradient to reach steady state. Once 24 hours had passed, the experiments began, with the data acquisition system taking measurements every minute. The values for each parameter were averaged over a 3 hour period. This process was repeated until complete steady-state was reached which was defined as the point when in five consecutive periods, the following requirements were met:

1. The average surface temperature of the specimen in the metering box did not vary by more than ±0.25°C
2. The average surface temperature of the specimen in the climate box did not vary by more than ±0.25°C
3. The average temperature of the air curtain (located 10 cm off the specimen interior surface of the specimen in the metering box) did not vary by more than ±0.25°C
4. The average temperature in the center of the wall did not vary by more than ±0.25°C

Once these requirements were met, data was collected for 5 consecutive 3 hour periods at a 1 minute time step and analyzed to determine the overall thermal resistance of the wall using Equation 1:

$$R = \frac{\Delta T}{\frac{q}{t \cdot A}} \tag{1}$$

where ΔT is the difference between the average hot side temperature and the average cold side temperature, q is the total heat input into the meter box, t is elapsed time, and A is the wall area specimen heated by the metering box.

4. Experimental Results

Before determining the thermal resistance, the surface temperatures and the interior wall temperatures at one of the monitoring points were plotted over the length of the test (Figure 4). From this chart, it can be seen that over the entire 15-hour period, there is no deviation in the temperature, with only some cycling present in the climate chamber which represent the cycling of the refrigeration unit.

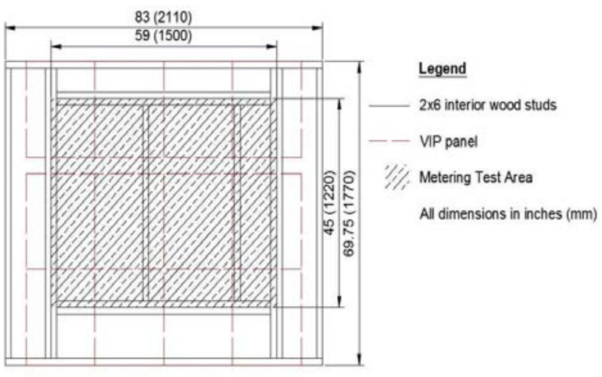

Figure 3: Schematic of the test specimen constructed for testing in the guarded hot box

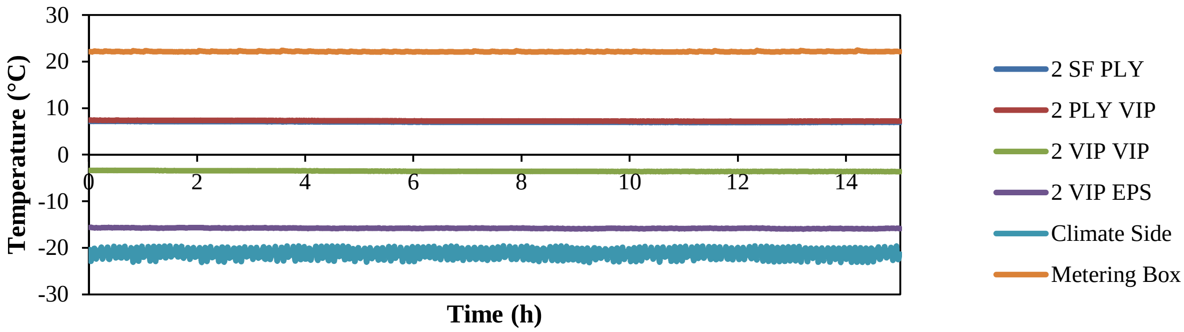

Figure 4: Surface and interior temperatures of the wall assembly during the 15 hour test (PLY – Plywood, SF – Spray Foam, EPS – Expanded Polystyrene)

A secondary check for steady-state conditions involved calculating any heat transfer across the guard box/meter box wall. For steady-state to be reached, according to ASTM C1363-11 standard [7], the total heat transfer across the interface must be less than 1% of the total heat input over the test period. This is measured by taking the surface temperature on both sides of each of the 5 surfaces, and with the metering box wall having a known R-Value of 0.92 m^2K/W. Using the measured average temperature difference of -0.005°C, the total heat transfer over the course of the test was found to be 0.4 Wh, which was less than 0.3% of the total heat input.

Over the 15-hour test period, 144.8 Wh ±1.1 Wh of heat was used to keep the metering box at a constant temperature. As there is negligible heat loss through the metering box, all heat must be lost through the specimen, and consequently, a total of 144.8 Wh ±1.1 Wh of energy flow through the wall specimen, through a measuring area of 1.83 m^2. The average temperature difference across the wall specimen was found to be 43.4°C ±0.6°C. Using these values, a final effective R-Value of the wall design was found to be 8.21 m^2K/W ±0.14 m^2K/W.

5. Experimental determination of the thermal resistance of a VIP panel

In addition to comparing the overall effective thermal resistance of the wall design, the thermal resistance of a single VIP panel was experimentally determined during the guarded hot box test. The temperature on both sides of two VIPs installed in series was recorded (3 temperatures in total) at 1 minute intervals for 100 minutes. In addition to the surface temperatures, a heat flux plate was installed in-line with the center of the double VIP layer and the thermal resistance of a VIP panel was determined using Equation 2:

$$R = \frac{\Delta T}{q''} \tag{2}$$

where ΔT is the difference in temperature across the panel, while q'' is the heat flux in W/m^2.

From this test, the average temperature difference across the first panel was found to be 10.5°C ±0.6°C and 12.3°C ±0.6°C across the second panel (from the inside of the wall out). At the same location, the average heat flux was found to be 4.22 W/m^2 ±0.21 W/m^2. From these values, the thermal resistances of the two panels were found to be 2.5 m^2K/W ±0.2 m^2K/W and 2.9 m^2K/W ±0.2 m^2K/W, respectively.

6. Comparison and analysis of the two testing methods

After testing the same wall design constructed to the same specifications using two different test methodologies, a comparison of the results was undertaken to determine the best method for experimentally evaluating wall designs that incorporate VIPs. Table 1 outlines the results from each of the two tests for the wall design and the VIP panels.

Table 1. Comparison of the test results

Test Methodology	Overall Effective R-Value of the wall (m^2K/W)	Average R-Value of the VIP panels (m^2K/W)
In-Situ Testing with Computer Modelling [4]	8.9	2.5
Guarded Hot Box	8.21	2.7
Percent Difference	-7.7%	8.0%

From these results, it can be seen that the experimentally determined effective thermal resistance of a wall design that incorporates VIPs, using a steady-state test in a guarded hot box reports values lower than those obtained through experimentally validated computer models. Although many factors could cause this lower thermal resistance, it is most likely the result of how the VIPs are accounted for in each method. When using the in-situ testing, a single thermal resistance for the center of the VIP was determined. This experimentally obtained thermal resistance of 2.5 m^2K/W was then used as a single continuous layer with no breaks (with the exception of the 4-inch break for fasteners) through the entire wall. Through literature and experience with further testing, it can be noted that VIPs do not have a constant thermal resistance across the panel, and actually decreases close to the edge, where a thermal bridges occurs as a result of two panels butted up to each other, as well as from the plasticized aluminum foil that creates a thermal bridge along the edge of each panel. As a result, a VIP cannot be accurately modelled as a single homogeneous material with properties equal to the center of panel as it does not accurately represent a layer of panels installed within a wall assembly.

When looking at the values obtained using both in-situ and steady-state measurements the discrepancy observed is within the experimental error and the discrepancies are most likely caused by small variations in the vacuum present in the panels, and subsequently their thermal resistance. Overall, based on the variations observed from panel to panel in previous studies and the larger experimental error as a result of the error on the heat flux plates and the smaller temperature difference, overall a good correlation was observed when measuring the thermal resistance of the VIPs only.

7. Conclusion

A comparison of testing methodologies was undertaken to determine the most appropriate method of experimentally evaluating the effective thermal resistance of a VIP wall assembly. It was determined that testing under steady-state conditions in a guarded hot box more appropriately evaluates wall designs incorporating many thermal bridges that cannot be easily modelled. Even when thermal bridges are not taken into consideration, the in-situ tests used to calibrate a computer model of the wall design were within 10% of the results obtained using the guarded hot box, making this a suitable alternative with decent accuracy when testing walls that have already been constructed, historic walls that cannot be replicated. When looking at determining the thermal resistance of a single point or material within a wall assembly, a negligible difference was observed between the two methodologies with the results of measuring a single VIP panel obtained in the two tests falling within the uncertainty of the test.

Future work will be conducted on determining a methodology for quantifying the effects of thermal bridges along VIPs, so that VIP layers can be accurately modelled and full scale testing is not required for every design.

Acknowledgements

The authors would like to acknowledge the financial support of the Natural Science and Engineering Research Council of Canada (NSERC) and Natural Resources Canada (NRCan).

References

[1] Natural Resources Canada - Office of Energy Efficiency, “Energy Use Data Handbook,” Ottawa, Canada, 2013.

[2] P. Mukhopadhyaya, D. MacLean, J. Korn, D. van Reenen and S. Melleti, “Building applications and thermal performance of vacuum inuslation panels (VIPs) in Canadian subarctic climate,” *Energy and Buildings,* vol. 85, pp. 672-680, 2014.

[3] “Team Ontario,” U.S. Department of Energy, [Online]. Available: http://www.solardecathlon.gov/past/2013/team_ontario.html.

[4] M. Schiedel, C. Cruickshank and C. Baldwin, “In-situ experimental validation of THERM finite element analysis for a high R-value wall using vacuum insulation panels,” in *7th International Conference on Energy Sustainability*, Minneapolis, Minnesota, 2013.

[5] “Standard Practic e for Determining Thermal Resistance of Building Envelope Components from In-Situ data” ASTM International, West Conshohocken, PA, 2007.

[6] “THERM,” Lawrence Berkeley National Laboratory (LBNL), [Online]. Available: http://windows.lbl.gov/software/therm/therm.html.

[7] “Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus,” ASTM International, West Conshohocken, PA, 2011.